

EXPERIMENTAL INVESTIGATIONS OF BACKWARD TRANSITION RADIATION FROM FLAT TARGET IN EXTREME ULTRAVIOLET REGION*

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Abstract

This report summarizes the results of an experiment dedicated to the observation of backward transition radiation in the EUV spectral region that was generated by an 855 MeV electron beam at a single layer molybdenum target. It was shown that the radiation measured in the EUV region was more intense than theoretically predicted. As a result the EUV radiation yield seems to be sufficient for standard beam profile diagnostic applications.

INTRODUCTION

Transverse profile diagnostics in modern electron linear accelerators as FELs or injector linacs is mainly based on optical transition radiation (OTR) as standard technique which is observed in backward direction when a charged particle beam crosses the boundary between two media with different dielectric properties. Advantages of OTR are the radiation generation directly at the screen boundary in an instantaneous emission process, a linear response, and the rather high light output emitted in a small lobe with an opening angle defined by the beam energy. However, there is a physical limitation that makes the method ineffective for modern beam diagnostics.

The experience from modern linac based light sources showed that OTR diagnostics might fail even for high energetic electron beams because of coherence effects in the OTR emission process. A cause of this coherent emission is the Microbunching Instability, i.e. some unstable micro structures in the electron bunch that compromise the use of OTR monitors as reliable diagnostic and may as well interfere with the FEL process in a malfeasant way. Coherent OTR (COTR) was observed e.g. at the Linac Coherent Light Source LCLS in Stanford (USA) [1] and at the free-electron laser FLASH at DESY in Hamburg (Germany) [2]. As consequence, for the new 4th generation light sources as the European X-FEL which is currently under construction in Hamburg [3] new reliable tools for transverse beam profile measurements are required.

In a previous paper [4] it was proposed to use backward transition radiation (BTR) in the Extreme Ultraviolet (EUV) region ($\hbar\omega \simeq 90$ eV) as possible tool for transverse bunch profile diagnostics. In this paper we report about the

first observation of BTR in the EUV region. The angular distribution of the radiation was measured in different geometries and compared for the optical and the EUV region.

THEORETICAL MODEL

Theoretical estimations were performed using a simple method of describing transition radiation following Ref. [5] as generated at an ideally reflecting molybdenum target. The real target properties were taken into account using Fresnel reflection coefficients. Because of the high reflectivity of molybdenum in the photon energy range of 30...100 eV for grazing angles $\alpha \leq 30^\circ$, the experiment was performed under these angles. The molybdenum permittivity in the photon energy range of 1...30 eV was taken from Ref. [7], in the range of 30...150 eV from Ref. [8]. More detailed explanations of the theoretical calculations for this experiment can be found in Ref. [6]. The results of these calculations together with experimental results are presented in the following.

EXPERIMENTAL SETUP

The experiment was carried out at the 855 MeV electron beam of the Mainz Microtron MAMI (Institute of Nuclear Physics, University of Mainz, Germany). Fig. 1 shows the scheme of the experimental setup. The electron beam with average beam current of 52 nA was used in macropulse operation, i.e. with a pulse duration of 0.8 sec and 3 sec spacing. The BTR target was mounted onto a goniometric stage together with wire scanners for transverse beam size diagnostics.

The BTR target was made of a 50 nm thin molybdenum

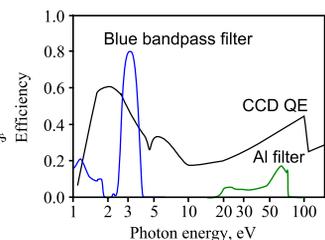
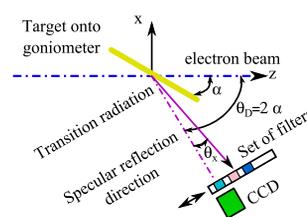


Figure 1: Experimental scheme. The y -axis is perpendicular to the drawing plane and points to the reader.

Figure 2: Transmission coefficients of the filters and CCD quantum efficiency.

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Table 1: Beam Sizes at the Target Location as Measured with the Wire Scanner

No.	Vert. FWHM, μm	Horiz. FWHM, μm
1	64.3	533
2	542	365
3	247	6111

layer (surface roughness better than 0.5 nm), evaporated onto a 0.5 mm thick silicon substrate (dimension 40 mm \times 10 mm). During the course of the experiment, it was oriented under two different grazing angles: $\alpha = 28.07^\circ$, $\theta_D = 2\alpha = 56.14^\circ$ (so-called “forward” geometry) and $\alpha = 67.5^\circ$, $\theta_D = 2\alpha = 135^\circ$ (so-called “backward” geometry).

The experiment was carried out using different beam sizes by changing the focusing lengths of upstream quadrupoles. Beam sizes were determined based on wire scanner measurements, the corresponding sizes (FWHM) are listed in Table 1. The resulting transition radiation angular distributions were recorded with a scientific grade CCD camera (ANDOR DO434-BN-932) with 1024 \times 1024 pixels and a pixel size of to 13 \times 13 μm^2 . Special feature of this CCD camera was the comparable high sensitivity in the photon energy range of 1 eV up to 10 keV. The distance from the target to the camera amounted 1010 mm.

A filter set mounted onto a movable holder was installed between target and camera. An optical bandpass filter ($\lambda = 400$ nm) was used to select visible light, and a 1.3 μm thick aluminum foil (consisting of two 0.65 μm thick layers) to discriminate against visible light contributions. Filter and CCD characteristics are shown in Fig. 2.

Further details of the experimental setup are given in Ref. [6].

EXPERIMENTAL RESULTS

All results presented in this section were calculated resp. normalized for a total number of $N_e = 10^{10}$ electrons (usual bunch population of modern accelerators). In addition, they are presented in the unit CCD counts per pixel, i.e. N_{ph}^{pix} . This quantity was obtained according to

$$N_{ph}^{pix} = N_e \int d\Omega \hbar d\omega \frac{d^2W}{\hbar d\omega d\Omega} E_{CCD}(\hbar\omega) T_i(\hbar\omega) \quad (1)$$

with $E_{CCD}(\hbar\omega)$ the CCD quantum efficiency and $T_i(\hbar\omega)$ the transmission function of the i -th filter. The solid angle $d\Omega$ is defined by the pixel size and the target-detector distance. The following values are compared for the theoretical and experimental distributions: distance between maxima, number of CCD counts, and distribution asymmetry. The latter is obtained according to:

$$A = \frac{I_l - I_r}{I_l + I_r} \quad (2)$$

with I_l and I_r the intensities of the left and right distribution maxima, respectively.

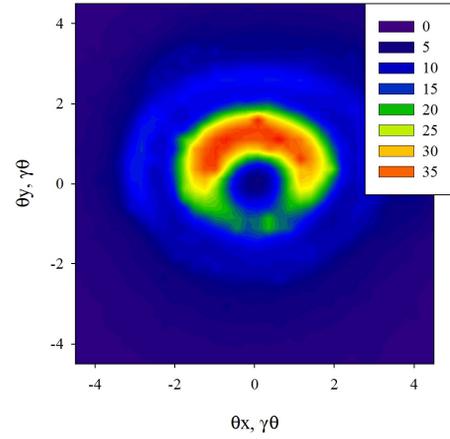


Figure 3: The spatial distribution of backward transition radiation obtained with the 400 nm bandpass filter.

One necessary prerequisite for beam diagnostic applications is that the radiation source should provide sufficient intensity. Therefore the intensity of transition radiation in the EUV and in the optical spectral region was compared. In a first step OTR passing the 400 nm-bandpass filter was measured. Fig. 3 shows an example of a recorded backward OTR distribution, using beam configuration No. 1 for a grazing angle $\alpha = 67.5$ deg.

Fig. 3 indicates that the obtained distribution is not symmetrical and posses some interference fringes. Probable reason for such asymmetry is that synchrotron radiation generated in upstream quadrupole magnets contributes to the measured intensity distribution. In order to investigate this effect more in detail, the measurements were repeated for different beam sizes and target inclination angles. The characteristics of the images obtained with the 400 nm filter are listed in Tab. 2.

It is striking that the distance between the maxima for the recorded distributions is larger than $2\gamma^{-1}$ in most cases. One possible explanation could be an influence of the pre-wave zone effect [9]. However, the reason is not yet confirmed and has to be investigated more in detail.

Table 2: Characteristics of Optical Transition Radiation for Different Beam Shapes Obtained with the 400 nm Filter

Beam	α , deg	Dist. between maxima, γ^{-1}	Asym., %	Total
No.1	28.07	x : 3.1	x : 1.8	$1.24 \cdot 10^6$
		y : 2.2	y : 33	
	67.5	x : 2.6	x : 0.7	
		y : 2.3	y : 36.5	
No.2	28.07	x : 1.9	x : 0.2	$1 \cdot 10^6$
		y : 2.4	y : 14	
	67.5	x : 2.1	x : 11	
		y : 2.3	y : 12	
No.3	67.5	x : 2.7	x : 5.7	$0.95 \cdot 10^6$
		y : 2.2	y : 1.6	

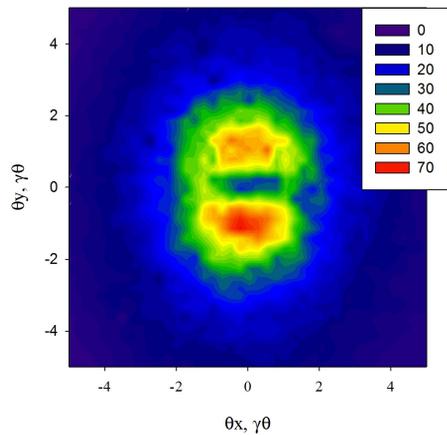


Figure 4: BTR angular distribution obtained with the Al filter at $\alpha = 28.07^\circ$.

Table 3: Characteristics of EUV Transition Radiation for Different Beam Sizes and the Al Filter

Beam	α , deg	Dist. between maxima, γ^{-1}	Asym., %	Total
No.1	28.07	x : 2.3 y : 2.2	x : 8.3 y : 5	$3.57 \cdot 10^6$
	67.5	x : 1.7 y : 2.1	x : 1.3 y : 3.3	$0.45 \cdot 10^6$
No.2	28.07	x : 1.7 y : 2.2	x : 1.9 y : 5.9	$2.44 \cdot 10^6$
	67.5	x : 1.4 y : 2.5	x : 0.7 y : 0.1	$0.38 \cdot 10^6$
No.3	67.5	x : 2.1 y : 2.1	x : 2.9 y : 1.5	$0.40 \cdot 10^6$

Comparing the expected intensities, the total number of CCD counts theoretically calculated in the angular range $-4.56\gamma^{-1} \leq \theta_x, \theta_y \leq 4.56\gamma^{-1}$ is equal to 3.98×10^6 for $\alpha = 28.07$ deg and 4.1×10^6 for $\alpha = 67.5$ deg.

Fig. 4 shows an example of an experimentally obtained BTR angular distribution for the grazing angle $\alpha = 28.07^\circ$ with the Al filter, using beam configuration No. 1.

It is obvious that the measured angular distribution in the EUV region is much closer to the theoretical one with respect to the shape. The results of the image analysis analogous to Tab. 2 are listed in Tab. 3. As can be seen the angular distributions in the EUV spectral region are more symmetrical than the ones in the optical spectral region. This may be explained by a stronger suppression of synchrotron radiation from the upstream magnets at these high photon energies.

The total number of CCD counts simulated theoretically in the angular range $-4.56\gamma^{-1} \leq \theta_x \leq 4.56\gamma^{-1}$, $-4.56\gamma^{-1} \leq \theta_y \leq 4.56\gamma^{-1}$ is equal to 0.58×10^6 for $\alpha = 28.07^\circ$ and 6×10^4 for $\alpha = 67.5^\circ$. From theory the intensity should be six times smaller than the one measured experimentally for beam No. 1 (comparing the total number of CCD counts), and a factor of 4.2 times smaller

for beam No. 2. The measured intensity is even larger than the theoretical one if we assume that our target has reflection coefficients equal to one in the whole energy range. In this case the calculated total number of CCD counts would amount $1.75 \cdot 10^6$ and would not depend on the grazing angle α .

CONCLUSION

It is important to point out that the properties of the measured BTR in the EUV region were observed reproducibly. The intensity of the measured radiation in this spectral region was higher than predicted from the model used, and therefore an application as basis for transverse beam profile diagnostics seems to be realistic in modern accelerators. The yield of EUV radiation obtained for a grazing angle of $\alpha = 28.07^\circ$ together with a $1.3 \mu\text{m}$ thick Al filter was larger than the one obtained in the optical spectral region with the 400 nm bandpass filter by a factor of approx. 2.5. The results obtained for the molybdenum target at a grazing angle $\alpha = 28.07^\circ$ with $1.3 \mu\text{m}$ thick Al filter allow to give an estimate for the EUV BTR yield of 3.5×10^{-4} photons/electron. The radiation measured in this spectral region is more symmetrical than in the optical spectral region, probably due to stronger suppression of parasitic synchrotron radiation. This may be an additional advantage for a diagnostics based on EUV transition radiation. As next step it planned to install a multilayer focusing mirror that render it possible to obtain beam profiles using EUV radiation, and to investigate the possibility of transverse profile measurements via imaging of the particle beam.

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